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Bound of earthquake input energy to building structure considering shallow and deep ground uncertainties

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ABSTRACT

The bound of earthquake input energy to building structures is clarified by considering shallow and deep ground uncertainties and soil–structure interaction. The ground motion amplification in the shallow and deep ground is described by a one-dimensional wave propagation theory. The constant input energy property to a swaying–rocking model with respect to the free-field ground surface input regardless of the soil property is used effectively to derive a bound. An extension of the previous theory for the engineering bedrock surface motion to a general earthquake ground motion model at the earthquake bedrock is made by taking full advantage of the above-mentioned input energy constant property. It is shown through numerical examples that a tight bound of earthquake input energy can be derived for the shallow and deep ground uncertainties.

1. Introduction

On March 11, 2011, the great Tohoku (Japan) earthquake attacked mainly the east part of Japan. Several giant tsunamis arrived the wide area of Tohoku district. That earthquake also shaked many tall buildings severely in Tokyo 200–500 km far from the fault region. However it should be reminded that a super high-rise building in the Osaka bay area was shaken more intensively regardless of the fact that Osaka is approximately 800 km far from the fault region. It has been reported [1,2] that the deep ground property of the building influenced such phenomenon. This fact clearly indicates that the deep ground property and its uncertainty should be investigated and included in the design of super high-rise buildings.

In the early history of seismic resistant design of building structures, the earthquake input energy was introduced as a stable and important measure together with deformation and acceleration [3]. It was known widely that, while deformation and acceleration are sensitive to the nature of earthquake ground motions, the input energy exhibits a stable characteristic and can take into account the effect of vibration duration. In addition, it has been understood well [4–6] that the input energy is suitable for soil–structure interaction problems because this problem can be expressed in a rational way by considering the exchange of energy between structures and soil.

There exist versatile researches so far on the topics of earthquake input energy (for example, [3,7–17]). However the earthquake input energy to soil–structure systems has not been thoroughly considered in literature except a few [6,18,19]. This may result from the fact that the behavior of a soil–structure system is quite difficult to describe in a simple way and its frequency-dependent characteristic causes a difficulty in incorporating its property in the time-history analysis for computation of input energy. In contrast to most of the previous works, the earthquake input energy is formulated here in the frequency domain [6,20–24] to facilitate the derivation of bound of earthquake input energy which is useful for the design of building structures under uncertain soil conditions.

In order to clarify the energy dissipation mechanism in the soil–structure interaction system, three kinds of input energy have been defined in [19], one to the overall soil–structure interaction system, one to the superstructure only and the other to the foundation-soil system. The difference between these three energies indicates the energy dissipated in the soil or that radiating into the ground. It has been demonstrated in [19] that the input energy expressions for the above-mentioned three systems or substructures can be of a compact form via the frequency integration of the product between

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the input component (Fourier amplitude spectrum) and the substructure model component (so-called energy transfer function). With the help of this compact form, it has been made clear that, when the ground surface motion is white (constant Fourier spectrum), the input energy to the swaying–rocking model is constant regardless of the soil property (input energy constant property). The upper bound of earthquake input energy to the swaying–rocking model has then been derived for the model including the surface ground amplification by taking full advantage of the above-mentioned input energy constant property and introducing the envelope function for the transfer function of the surface ground amplification.

In this paper, the theory developed in [19] (white ground motion at the engineering bedrock) is extended to a general earthquake ground motion model at the earthquake bedrock [25] by taking into account the overall ground motion amplification including the effect of shallow and deep ground with uncertainties. It is shown that the proposed upper bound of input energy is tight owing to the constant input energy property introduced in [19] for white free-field ground surface motion. It is expected that the consideration of uncertainties in shallow and deep ground properties in the evaluation of earthquake input energy to building structures enhances the reliability of the seismic safety of the building structures under uncertain environments.

2. Earthquake input energy to SR model in time domain subjected to free-field ground motion

Consider a one-story shear building model (mass m, stiffness k, damping coefficient c), as shown in Fig. 1, supported by swaying and rocking springs k_H, k_R and dashpots c_H, c_R and subjected to a horizontal acceleration $\ddot{u}_g(t)$ at the free-field ground surface. This model is a simplest model for representing the soil–structure interaction and called the SR (swaying–rocking) model. Let m_0, I_{R0}, L denote the foundation mass, its mass moment of inertia and the height of the structural mass from the base. The moment of inertia of structural mass is I_R.

Let u_S, θ_R denote the foundation horizontal displacement and its angle of rotation relative to the free-field. The horizontal displacement of the super-mass relative to the foundation without rocking component is denoted by u. The equations of motion of the model in the time domain are expressed as

$$\mathbf{M}\ddot{\mathbf{u}}+\mathbf{C}\dot{\mathbf{u}}+\mathbf{K}\mathbf{u}=-\mathbf{M}\mathbf{r}\ddot{u}_g \tag{1}$$

where

$$\mathbf{M}=\begin{bmatrix} m & m & Lm \\ m & m_0+m & Lm \\ Lm & Lm & L^2m+I_R+I_{R0} \end{bmatrix}, \mathbf{K}=diag\begin{pmatrix} k & k_H & k_R \end{pmatrix},$$

$$\mathbf{C}=diag\begin{pmatrix} c & c_H & c_R \end{pmatrix}, \mathbf{u}=\begin{pmatrix} u & u_S & \theta_R \end{pmatrix}^T, \mathbf{r}=\begin{pmatrix} 0 & 1 & 0 \end{pmatrix}^T \tag{2a–e}$$

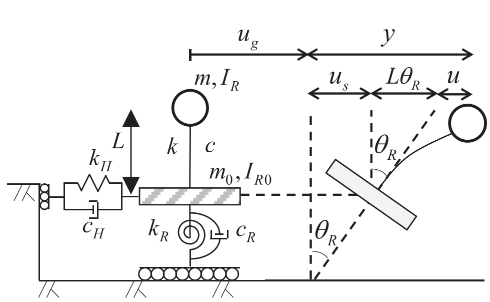

Fig. 1. Swaying–rocking model subjected to free-field ground motion.

$\mathbf{C}$ represents the structural damping and soil damping. Let us introduce the absolute horizontal displacement y of the super-mass as

$$y=u+u_S+L\theta_R \tag{3}$$

As shown in [19], the earthquake input energy E_I^A to the SR model is expressed as

$$E_I^A=-\int_0^\infty \dot{\mathbf{u}}^T\mathbf{M}\mathbf{r}\ddot{u}_g dt \tag{4}$$

3. Earthquake input energy to SR model in frequency domain

The earthquake input energy to a linear elastic structure can also be expressed in the frequency domain [12,18,21–24]. The derivation for the model shown in Fig. 1 can be found in [19]. Therefore only the final result is shown in the following:

Let U, U_S, Θ_R, Y, U_g denote the Fourier transforms of u, u_S, θ_R, y, u_g and H, H_S, H_R, H_Y denote the transfer functions of u, u_S, θ_R, y to $\ddot{u}_g$ as follows:

$$U/\ddot{U}_g=H(\omega),\quad U_S/\ddot{U}_g=H_S(\omega),\quad \Theta_R/\ddot{U}_g=H_R(\omega),\quad Y/\ddot{U}_g=H_Y(\omega) \tag{5a–d}$$

The earthquake input energy to the SR model in the frequency domain can be obtained as

$$E_I^A=\int_0^\infty F_A(\omega)\left|\ddot{U}_g\right|^2 d\omega \tag{6}$$

where $F_A(\omega)$ is called the energy transfer function of the SR model expressed by

$$F_A(\omega)=\frac{1}{\pi}\mathrm{Re}\left[\frac{1}{\mathrm{i}\omega}\left\{m_0\left(\omega^2H_S-1\right)+m\left(\omega^2H_Y-1\right)\right\}\right] \tag{7}$$

Re[ ] denotes the real part.

4. Property of earthquake input energy to SR model subjected to white-noise-like free-field input

An example of the energy transfer function $F_A(\omega)$ was shown in [19]. That function exhibits a peak at the fundamental natural frequency of the SR model. Consider the earthquake input energy to the overall SR model subjected to a white-noise-like free-field input with $\left|\ddot{U}_g(\omega)\right|=1$. This quantity is called the 'scaled earthquake input energy' for the free-field input and can be evaluated by

$$J_{SR}^F=\int_0^\infty F_A(\omega)d\omega=\frac{1}{2}\sum m_i \tag{8}$$

The summation is extended to the superstructure masses and the foundation mass. Eq. (8) can be proved by taking into account that a white-noise-like free-field input with $\left|\ddot{U}_g(\omega)\right|=1$ is equivalent to the impulsive loading with the initial velocity of 1 in time domain [19,24].

5. Earthquake input energy to SR model subjected to engineering bedrock input

Consider a ground model consisting of a uniform surface ground (for example GL – 0 m to GL – 20 m) and a uniform engineering bedrock beneath it. Only vertical wave propagation is considered.